

Unbalanced Traffic Volumes at Roundabouts

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ABSTRACT

The analysis of traffic flow at roundabouts has often been simplified by treating the roundabout as a series of isolated T-intersections with no interaction between the entering traffic streams from the various approaches. More recently, the effects of significant differences in approach volumes have been taken into account—as may be found in the latest version of the SIDRA software package. Such differences in approach volumes—or imbalances as they are termed in this paper—can have a significant effect on delay and capacity estimates for any given total volume of traffic entering a roundabout. The SIDRA package endeavours to take into account the effect of one approach volume dominating the other approaches but it does not appear to be directly responsive to the actual location of the dominant approach relative to any other approach being analysed. However, it was found in this research—which used the simulation program TRACSIM—that the delay on any given approach appears to be sensitive to a change in the balance of the circulating flows. For example, if most of the flow circulating past an approach originates from the first approach upstream then the average delay tends to be high. However, if the same volume of circulating traffic had originated from the second approach upstream then the average delay would tend to be low. Consequently, the “origin-destination” as well as the magnitude of the various approach volumes can be expected to affect the performance of a roundabout. The lack of appropriate field data limits the result of this study to a comparison between simulated and analytical models.

1. INTRODUCTION

Roundabouts have the potential to resolve various traffic flow problems—such as dealing with conflicting manoeuvres and reducing speeds in sensitive areas—but they must be used as a palliative not a panacea. If roundabouts are used inappropriately then poor performance will result and this has been found to lead to resistance to their use (Krogscheepers and Roebuck 1994). Consequently, it is considered important to understand the manner in which roundabouts respond to various demand patterns so that they are not used under inappropriate conditions.

A typical and obviously inappropriate set of conditions is where the traffic volume on one approach is so high that it effectively precludes vehicles from entering at any other approach. Under these conditions the total volume of traffic trying to use the roundabout may be quite moderate but inordinate delays would result on some approaches due to this large imbalance in the approach volumes. An obvious question arising here is at what level of an imbalance in flows are unacceptable delays likely to occur? Many analysis methods

cannot answer this question since they effectively treat each approach as an isolated T-intersection. In this paper, an overview is first given of recent research work and software packages—notably SIDRA—that take into account an imbalance in flows. Subsequently, the results from SIDRA are compared with results from the simulation program TRACSIM that was validated for roundabout operations in South Africa (Krogscheepers 1997).

It must be appreciated that the results presented are derived from simulation models with all of the attendant advantages and disadvantages. Moreover, due to the difficulty of obtaining field data for such a wide spectrum of flow conditions at a single roundabout, these results could not be verified with field data. However, the results obtained from the TRACSIM simulations clearly indicate that the source of conflicting traffic volumes has a marked effect on delay patterns and should be considered in analysis and as topics for further research. The definition of imbalanced flow in this research differs from that used elsewhere—for example in SIDRA.

2. DEFINITION OF UNBALANCED FLOW

In this research, the ratio-of-imbalance (ρ_i) was defined as the proportion of circulating traffic originating from the first upstream approach of the subject approach. For the northern approach, the ratio-of-imbalance (ρ_n) is defined as follows (see Figure 2 for definition of flows):

$$\rho_n = \frac{Q_{wn}}{Q_{wn} + Q_{sn} + Q_{en}} = \frac{Q_{wn}}{Q_{nc}} \quad (1)$$

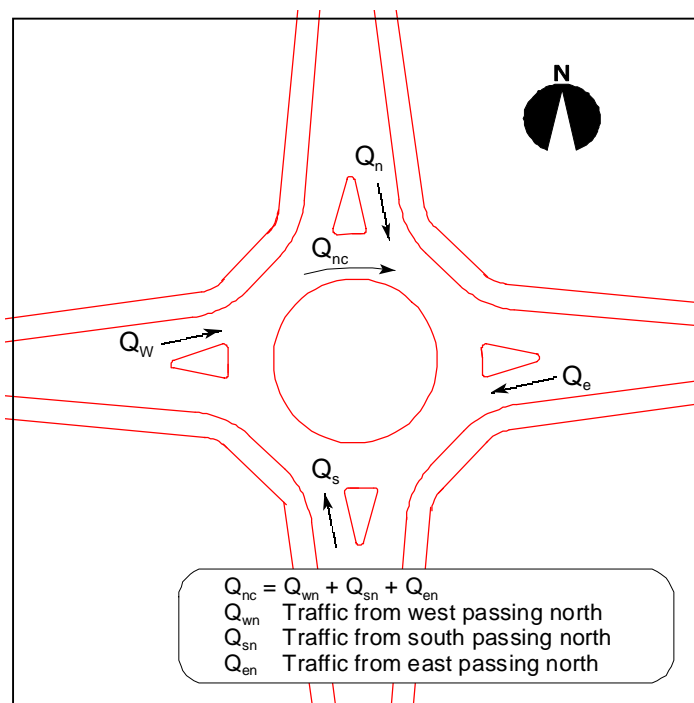


FIGURE 1 Definition of unbalanced flows.

As this research was conducted in South Africa, this definition applies to driving on the left-hand side of the road and traffic circulating clockwise. A similar definition applies to the three other approaches of the roundabout. Typically, the U-turn volumes are negligible and in the above definition, only the right turns from south and the through and right-turning vehicles from west would be included in the circulating flow past north. A balanced approach would have $(\rho_i) = 0.5$, which means that the circulating traffic at the approach would consist of 50% from the first upstream approach and 50% from the second upstream approach. A totally unbalanced approach would have $(\rho_i) = 0$ or 1 for each approach. With $(\rho_i) = 0$ all the circulating traffic originates from the second upstream approach and none from the first upstream approach while for $(\rho_i) = 1$, all the circulating traffic originates from the first upstream approach.

This definition is different from that used by Akçelik et al. (1995) for (p_{cd}) where the proportion relates to the circulating flow originating from the dominant approach and hence the value of (p_{cd}) will always be equal to or greater than a half. In this research, the ratio of imbalance (ρ_i) can vary between zero and one. The reason for the difference in definition from that defined by Akçelik et al. (1995) is related to the possible difference in gap acceptance behavior. In previous research (Krogscheepers and Roebuck 1998), it was postulated that the gap acceptance behavior of drivers depends on the origin of the next conflicting vehicle, i.e., whether that vehicle is entering from the previous upstream approach or circulating around the roundabout (see Figure 2). Therefore, it is possible that a dominant flow from the first upstream approach has a different effect on approach behavior at a subject approach than a dominant flow from the second upstream approach.

3. REVIEW OF OTHER WORK

Most available analytical and empirical roundabout analysis methods and most literature on the subject of roundabout operational analysis treat a roundabout as a series of T-intersections with no interaction between the approaches (Austroads 1993). Therefore, for most of the available methods, the origin of the conflicting circulating flows does not affect the capacity and delay estimates of a roundabout approach. The only exception is the analytical techniques included in the latest version of SIDRA (Akçelik and Besley 1998), the Australian software package for isolated intersection analysis. According to Akçelik et al. (1995), this is not true in reality as many real life roundabouts indicate that capacities could be over-predicted with an imbalance of approach flows, especially at multi-lane circles. Chung et al. (1992) and Chung (1993) showed with the aid of preliminary simulations that the arrival approach patterns affect approach capacities and that capacity decreases with an increase in the imbalance of approach flows. The highest capacities were obtained with well-balanced flows.

The work by Chung (1993) on unbalanced flows was expanded and is now included in the latest version of SIDRA and is reported on in detail by Akçelik et al. (1995) and Akçelik (1998). The basis of this method is to reduce the approach capacity, which is based on basic gap acceptance theory, to allow for the effects of imbalance in traffic volumes and also for the approach queuing characteristics. SIDRA is also one of the few analytical models that employ a variable gap acceptance model for capacity analysis. The critical gap used in SIDRA, not only varies as a function of the geometric layout of the

roundabout, but also as a function of the conflicting circulating stream volume. In the event of unbalanced circulating flows, however, the critical gap should remain constant because there is no variation in the conflicting stream volume or the geometric layout of the roundabout.

The method used in SIDRA (Akçelik 1998) is based on a factor (f_{od}) to reduce the basic gap-acceptance capacity (Q_g) to allow for the effects of the unbalanced flows and the approach queuing characteristics of the traffic in the circulating traffic stream. The roundabout approach capacity (Q_e) is defined as:

$$Q_e = \max (f_{od} Q_g, Q_m) \quad (2)$$

where Q_m is the minimum approach capacity and the factor (f_{od}) defined as follows:

$$f_{od} = 1 - f_{qc} (p_{qd} p_{cd}) \quad (3)$$

The two factors (p_{cd}) and (p_{qd}) that are used to reduce the approach capacity are:

1. the proportion (p_{cd}) of the total circulating stream flow that originated from the dominant approach, and
2. the proportion queued (p_{qd}) of the part of the circulating stream that originated from the dominant approach.

The dominant approach is defined as the approach with the highest value of ($p_{cd} \times p_{qd}$). The product of the two ratios represents the proportion of the total circulating flow that originated from the dominant approach and which were queued on that approach. In the case of multi-lane approach roads, the value of ($p_{cd} \times p_{qd}$) is determined by using a flow-weighted average of individual lanes. In this paper a different definition is used to describe an imbalance of circulating flows (see Section 3) and only the single lane case is considered. The factor (f_{qc}) as used in SIDRA is a calibration parameter and for single lane roundabouts it is given by:

$$f_{qc} = \begin{cases} 0.04 + 0.00015q_c & \text{for } q_c < 600 \\ 0.0007q_c - 0.29 & \text{for } 600 \leq q_c \leq 1200 \\ 0.55 & \text{for } q_c > 1200 \end{cases} \quad (4)$$

It is clear from the above that the greater the proportion of circulating traffic from a single upstream approach and the greater the proportion of these vehicles queuing prior to entering the roundabout, the lower the factor (f_{od}) will be and the lower the entering capacity. A constant conflicting circulating traffic volume of say 500 vehicles per hour could result in different approach capacities for a subject approach depending on the origins of the 500 vehicles and the queues experienced on the dominant approach.

The work by Akçelik et al. (1995) is based on simulations obtained from MODEL C (Chung 1993), a simulation program which simulates traffic entering a roundabout based on a critical gap that varies with the volume of the conflicting stream. However, the model is blind to the origin of the circulating/conflicting vehicles, i.e., whether the next

conflicting vehicle is entering from the adjacent upstream approach or whether it has entered from a previous upstream approach.

4. RESEARCH METHODOLOGY

4.1 Simulation Model

This research is based on computer simulations with the program TRACSIM that was developed as part of an investigation into the operation of roundabouts under South African conditions (Krogscheepers 1997). TRACSIM is a microscopic computer simulation model of isolated single-lane roundabouts. The simulation program was developed to assist in the data collection process, specifically because of the lack of South African roundabouts operating under high volume demands. The simulation program was calibrated and validated based on data sets obtained from four single-lane roundabouts.

Three different gap acceptance models were tested during the validation process of the model. The first gap acceptance model was based on the standard gap acceptance process based on time headways, while the second method employed a gap acceptance process based on distance gaps between consecutive conflicting vehicles. Both of these gap acceptance models resulted in successful validation of the model. The distance-based model gave results at least as good as the time-based model. A third model that yielded less successful results was based on a probability of acceptance method, which was based on the position of the conflicting vehicle. For both the time gap and distance gap acceptance models, critical time and distance gaps were defined based on observed data at each of the three roundabouts. This, together with other observations such as speeds, move-in times, traffic volumes and the geometric features of the roundabout were used to simulate the operations at the roundabouts.

During the data collection stage for the validation of TRACSIM an effort was made to differentiate between, amongst others, gaps accepted in entering traffic and gaps accepted in circulating traffic (see Figure 1). Where entering traffic is defined as traffic originating from the first upstream approach to the subject approach and circulating traffic as all traffic that originated from approaches prior to the first upstream approach. From the observations at the roundabouts, it was noted that sometimes, conflicting entering traffic, upstream of the first upstream approach's yield line (say on west approach) could occasionally result in the gap being rejected (on north approach). This decision was not only based on the distance to the conflicting vehicles, but also on whether the conflicting vehicles were stationary at the yield line, starting to move, or were moving at a significant speed into the roundabout.

According to the time-based lag and gap observations no obvious difference could be established in the gap acceptance characteristics of drivers, accepting gaps in a stream of entering traffic or in a stream of circulating traffic. Therefore, the model was validated employing a time-based gap acceptance model that was "blind" to the origin of the next conflicting model. However, for a distance-based gap acceptance model it is essential to differentiate between entering and circulating conflicting vehicles—especially for stationary, conflicting vehicles waiting for an acceptable gap on the adjacent upstream approach. These

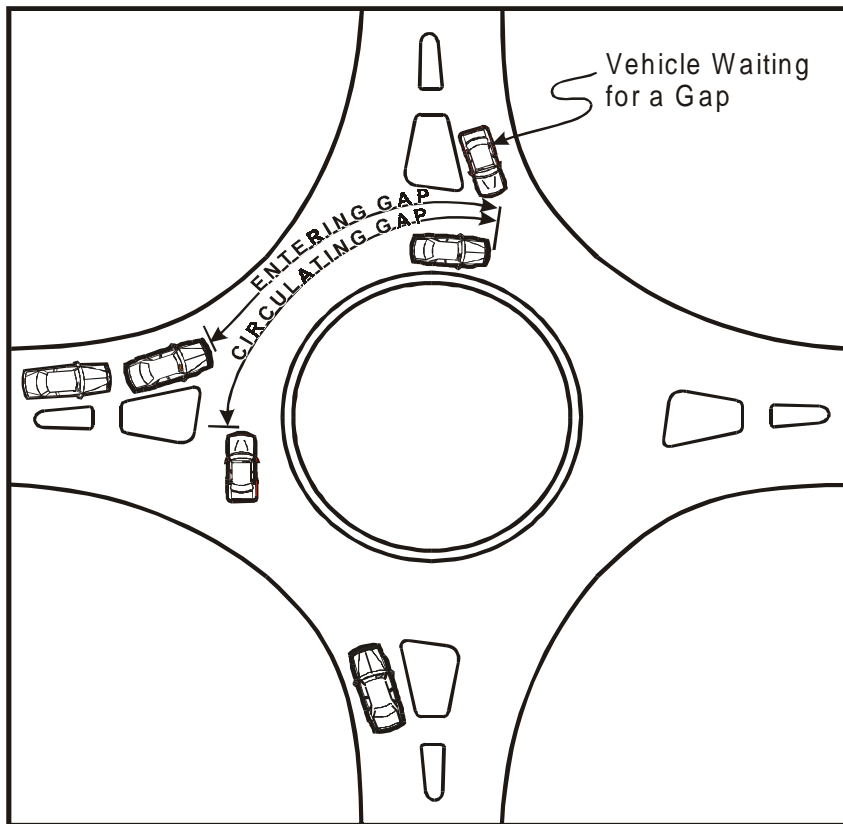


FIGURE 2 Circulating versus entering gaps.

entering vehicles on the first upstream approach could fall within the critical distance of a entering driver, resulting in “acceptable” gaps being rejected. To allow for this effect in the simulation model, observed probabilities of acceptance were used for “entering” conflicting vehicles. In the model, the observed critical distance was used for the gap acceptance process in both the entering and circulating conflicting traffic, but a correction was made for entering gaps. Whenever the critical distance gap of a driver waiting for a gap was smaller than the available gap in the conflicting “entering” traffic stream, the gap was accepted. However, with a critical gap greater than the presented gap in the entering traffic, it was not summarily rejected. Instead, the position of the conflicting vehicle was first evaluated. If this vehicle had already started to enter the roundabout, the decision was upheld and the gap rejected. However, if the conflicting vehicle was stationary at the yield line or moving upstream of the yield line, a probability of acceptance was used to decide whether the gap should really be discarded or if sufficient reason existed to accept the gap.

Employing TRACSIM, synthesized sets of traffic demand volumes were used to test the effect of an imbalance in conflicting volumes. The analysis concentrated on one approach of a roundabout for which the approach and circulating flows were maintained at a constant flow, while the ratio-of-imbalance of the circulating stream was varied. The performance of the subject approach, in terms of average delay per vehicle, was compared for different ratios-of-imbalance.

The performance of the subject study approach was evaluated in terms of “queuing delay.” Queuing delay is defined as the time spent in a queue. This time excludes the major acceleration and deceleration. This is equivalent to the control delay, as defined in the

1997 *Highway Capacity Manual*, less geometric delay and the major stop/start delay. The latest version of SIDRA only allows for the calculation of control delay (overall delay including geometric delay) and stop-line delay (overall delay excluding geometric delay). Therefore, in an effort to compare the simulated queuing delays as estimated by TRACSIM to the stop-line delays as obtained from SIDRA, the effect of the major stop/start delay had to be taken into account. Typically the major stop/start delay increases the queuing delay with approximately 30 percent (HCM 1994; Van As and Joubert 1993). Therefore, the SIDRA stop-line delays were adjusted down with a factor of 30 percent to obtain an estimate of queuing delay that is comparable with the TRACSIM queuing delays. Delay in this paper refers to queuing delay unless otherwise indicated.

4.2 Test Roundabout

An actual roundabout located in a large residential area—Chatsworth near Durban—was used for this research. The Chatsworth roundabout is a four-legged intersection with single approach and exit lanes on each approach. It has an inscribed circle diameter of 50 meters with a central island diameter of 36.2 meters and a 6.9 meters circulating carriageway. The approaches are slightly flared, but insufficiently to allow for two vehicles at the yield line (Figure 3). The number of pedestrians at the roundabout was insignificant.

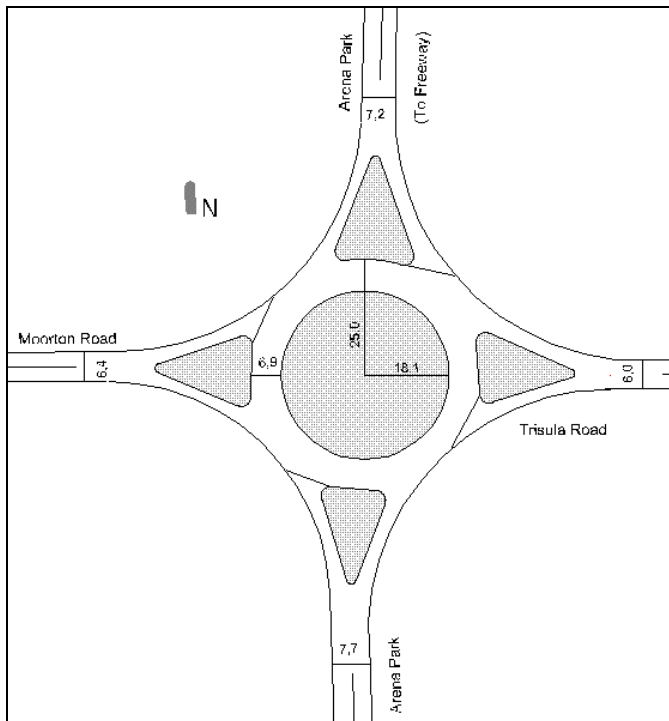


FIGURE 3 Test Roundabout—Chatsworth.

4.3 Data Sets

Two synthesized data sets of demand traffic flows were used for the simulation. In defining the demand flows, the first objective was to vary the balance of conflicting circulating flows passing one approach while maintaining a constant circulating volume and entering volume. In addition, care was exercised to prevent over-saturation at any of the other approaches while maintaining a relatively constant total approach flow to the roundabout. The two sets of input data are summarized in Tables 1 and 2. Both of these data sets show a constant 600 vehicles per hour entering on the northern approach and 700 vehicles per hour circulating past the approach. By varying the approach flows from south and west, the ratio-of-imbalance for the northern approach was varied between zero and one in increments of one-tenth, while the ratio-of-imbalance at all the other approaches were kept relatively constant. The main difference between the two data sets is the amount of right turn traffic from east. In the second set, the right turn volumes from the east were eliminated completely. The right turns from east conflict with both entering traffic from south and from west and the effect of these right turns was thus eliminated.

TABLE 1 Data Set No. 1

North			East		South		West		Total
Through	Right	(ρ_n)	Through	Right	Through	Right	Through	Right	
600	—	1.0	10	300	220	10	350	340	1830
600	—	0.9	10	300	220	80	310	310	1830
600	—	0.8	10	320	200	150	300	250	1830
600	—	0.7	10	340	180	200	280	220	1830
600	—	0.6	10	340	180	280	220	200	1830
600	—	0.5	10	340	180	340	180	180	1830
600	—	0.4	10	390	130	420	140	140	1830
600	—	0.3	10	420	100	480	110	110	1830
600	—	0.2	10	350	80	550	80	70	1740
600	—	0.1	10	350	50	630	30	40	1710
600	—	0.0	10	350	50	690	5	5	1710

TABLE 2 Data Set No. 2

North			East		South		West		Total
Through	Right	(ρ_n)	Through	Right	Through	Right	Through	Right	
600	—	1.0	—	—	220	10	350	340	1520
600	—	0.9	—	—	220	80	310	310	1520
600	—	0.8	—	—	200	150	300	250	1500
600	—	0.7	—	—	180	200	280	220	1480
600	—	0.6	—	—	180	280	220	200	1480
600	—	0.5	—	—	180	340	180	180	1480
600	—	0.4	—	—	130	420	140	140	1430
600	—	0.3	—	—	100	480	110	110	1400
600	—	0.2	—	—	80	550	80	70	1380
600	—	0.1	—	—	50	630	30	40	1350
600	—	0.0	—	—	50	690	5	5	1350

No left turns on any of the approaches were simulated. This was done, not only to reduce the possible effect of left turns on entering traffic but also because the left turns do not contribute to the circulating traffic volumes. During the validation of TRACSIM (Krogscheepers 1997) it was found that the effect of exiting traffic had a negligible effect on the gap acceptance characteristics of entering drivers from the same approach. Each of the above sets of flows was simulated for more than seven hours to obtain an average condition for the prevailing geometric and traffic flow conditions.

4.4 Comparison with SIDRA

The average queuing delay as obtained from the TRACSIM simulation was compared with estimates of delay based on the SIDRA method. The SIDRA analysis was based on the Chatsworth roundabout and the same demand traffic flows as summarized in Tables 1 and 2. The SIDRA estimates were based on three data sets for different critical gap and move-in time estimates. In previous research (Krogscheepers 1997) it was shown that the SIDRA method, significantly underestimates the delay at roundabouts in South Africa when the model's default critical gap and move-in time values are used. Therefore, in addition to the SIDRA estimates based on the model's 'default' critical gap and move-in time values, a second SIDRA estimate was conducted based on the actual "observed" critical gap and move-in times. These are the critical gaps and move-in times observed at the Chatsworth roundabout.

However, the SIDRA estimates based on the observed critical gap and move-in times significantly overestimated the TRACSIM delays. Therefore, a third SIDRA estimate was conducted that was based on a "calibrated" value for the critical gap. The "calibrated" value for the critical gap was selected such that the estimated SIDRA delays were comparable with the TRACSIM simulated delays. This was done for at least the balanced flow scenario. The "default," "observed" and "calibrated" values for the critical gap and move-in times as used in the SIDRA analysis of the northern approach to the test roundabout are summarized in Table 3.

5. SIMULATION RESULTS AND DISCUSSION

The average queuing delay per vehicle for the northern approach of the test roundabout, employing a distance-based gap acceptance model and based on the first set of input flows (see Table 1), is summarized in Figure 4. In Figure 4, the TRACSIM simulated delays are also compared with three SIDRA delay estimates. The three SIDRA scenarios vary in terms of the input values for the critical gap and move-in times (see Table 3).

TABLE 3 Data Input Values for the Three SIDRA Scenarios

	SIDRA "Defaults" (Seconds)	"Observed" Values (Seconds)	"Calibrated" Values (Seconds)
Critical Gaps	3.9	4.5	4.2
Move-in Times	2.2	2.7	2.7

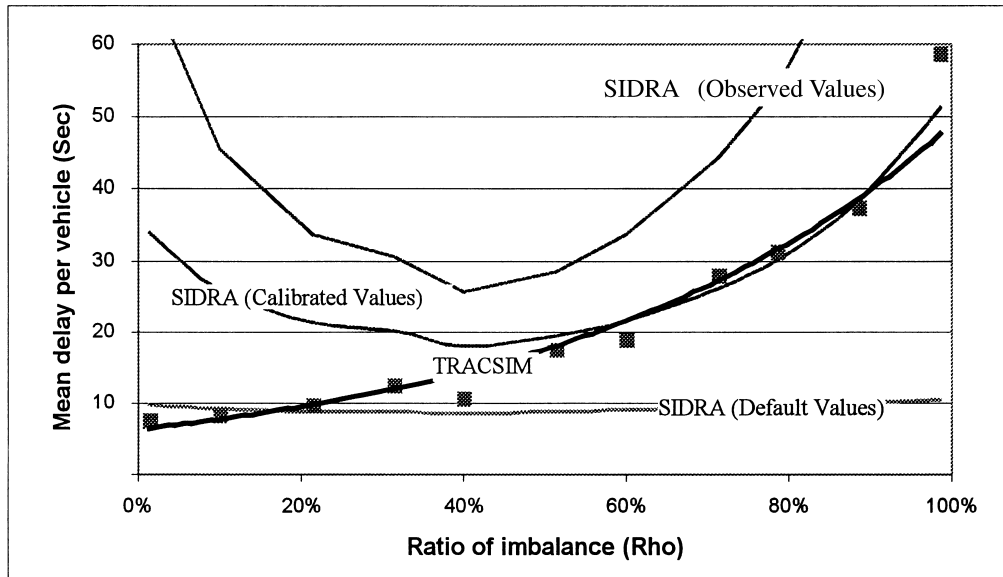


FIGURE 4 Effect of unbalanced flows (data set No. 1).

The TRACSIM results clearly show an increasing trend in average delay per vehicle as the ratio-of-imbalance increases from zero to one. The approach delay is at a maximum when all the conflicting circulating vehicles originate from the neighboring upstream approach (gaps accepted in entering traffic). With conflicting circulating vehicles originating from the southern approach, the distribution of available gaps and/or the gap acceptance characteristics of entering drivers result in more gaps being accepted and hence lower delay per vehicle. The distance-based gap acceptance method is “blind” to speed. Slower vehicles will occupy the critical area for a longer period of time than a faster vehicle, resulting in longer delays to the vehicle waiting for a gap. Entering vehicles have to accelerate from a stationary position or slow speed to their desired circulating speeds. This results in lower average speeds of entering vehicles inside the critical gap area than the comparable speeds of circulating vehicles.

This relationship between delay and the ratio-of-imbalance is only illustrated qualitatively and is not quantified. Therefore, the trend line fitted through the simulated data points is only for illustrative purposes. From the simulation results it is clear that an imbalance in circulating flows can have a significant impact on the approach capacity. An imbalance in conflicting flows can result in over-saturated conditions on a roundabout approach, while similar more balanced conflicting volumes can result in acceptable degrees of saturation. These results highlight the interdependency of roundabout approaches, and that a roundabout should not be analyzed as a series of independent T-intersections. Clearly, the interaction between approaches depends on the size of the roundabout and would be absent at the older rotary type traffic circles.

The comparison of the simulated delay with that of SIDRA reveals a number of interesting observations. It is clear the SIDRA estimates based on its default values for critical gaps and move-in times are significantly lower than that estimated by the TRACSIM simulation model. On the other hand, based on the “observed” critical gap and move-in

data, the SIDRA delay estimates are significantly higher than that of TRACSIM. Calibrating SIDRA to present estimates which are comparable with the TRACSIM simulation shows significant agreement for ratios-of-imbalance greater than 50 percent. However for ratios-of-imbalance less than 50 percent, SIDRA mirrors the delays for ratios greater than 50 percent, while the TRACSIM delays continue to decline. The mirror effect is due to the definition of an imbalance in terms of the dominant approach. The TRACSIM results suggest that this should be reconsidered and that the origin of conflicting circulating vehicles plays a more significant role.

The simulation results based on the second set of traffic data (see Table 2) are summarized in Figure 5. The estimated delay increases from a low point for a zero ratio-of-imbalance to a maximum for a ratio-of-imbalance equal to one. When comparing the TRACSIM estimates as summarized in Figure 4 with those in Figure 5, it is clear that the elimination of the right turn volumes from east does not have a significant effect on the average delay per vehicle on the northern approach. Eliminating the right turn volumes from east does not affect the number of conflicting vehicles circulating past north, but affects the ratio-of-imbalance for west and south. Therefore, it is concluded that the delay on an approach does not change significantly if the ratio-of-imbalance changes at an upstream approach, i.e., the delay at north is not affected by a change in the ratio-of-imbalance at west or south.

Again, the SIDRA estimates based on the “default” critical gap and move-in times are lower than the TRACSIM estimates. However, the SIDRA estimates based on the observed critical gap and move-in times are much closer to the TRACSIM delays than the comparison in Figure 4 that was based on the first data set. Therefore, a “calibrated” SIDRA estimate was not made. However, the SIDRA estimates are significantly different from those summarized in Figure 4 and the mirror effect around the 50 percent ratio-of-imbalance is not repeated.

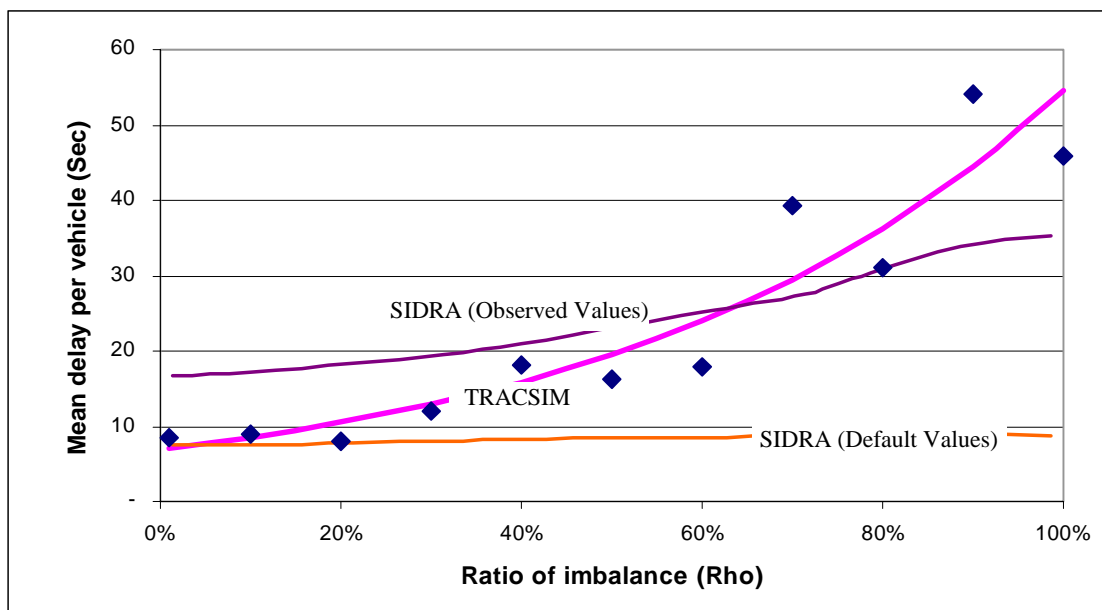


FIGURE 5 Effect of unbalanced flows (data set No. 2).

The reasons for the difference in the SIDRA estimates are not obvious. Right turning traffic from east exiting at north could have an affect on the entering traffic from north but this affect was ignored in the SIDRA analysis. The basic gap-acceptance capacity (Q_g) as used in Equation (1) is independent of anything happening upstream of the entry approach. Therefore, the difference in the SIDRA estimates is possibly limited to the factor (f_{od}) as used in Equation (1). As explained in Section 2, (f_{od}) is a function of the two proportions (p_{cd}) and (p_{qd}), which according to their definitions are dependent on the proportion of circulating vehicles past the subject approach and the proportion of the circulating vehicles that were queued prior to entry into the roundabout. These two proportions are also independent of any circulating flow conditions upstream of the subject entry.

6. SUMMARY OF FINDINGS

Most models for analyzing traffic flow at roundabouts are not responsive to the effects of an imbalance in approach volumes. However, the latest version of the SIDRA software package endeavours to take into account the effect of one approach volume dominating the other approaches. The effect of the resultant imbalance is represented by reducing the approach capacity. In this research, a microscopic simulation model TRACSIM was used to study the effects of an imbalance in approach volumes. In effect TRACSIM, models the behavior of each driver entering a roundabout—based on distance gaps and also the position and origin of conflicting vehicles. The results of this research clearly indicate that for a given total volume of traffic entering a roundabout, the delay on each approach will vary with the level of balance in the circulating flow. It appears that the delay on an approach is sensitive to the origin of conflicting traffic. In particular it appears that delay on approach is strongly affected by traffic flows at the first approach upstream and hence that “dominance” per se—as represented in SIDRA—is not the sole factor to be considered. Consequently, this research indicates that an imbalance in flows needs to be defined according to the proportion of conflicting traffic that originates from the first approach upstream of the subject approach.

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